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Evaluation of Radioactive Source Terms in the System-Integrated Modular Advanced Reactor

Seong Uck Kim and Chang Sun Kang
Seoul National University
San 56-1, Shillim-dong, Kwanak-gu, Seoul 151-742, Korea

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Abstract

A 330 MWt-sized multi-purpose integral-type reactor, SMART is under development in Korea for the use of nuclear energy other than electricity generation. In this study, various radioactive source terms are estimated for SMART. SMART is different from conventional reactor concepts in operation and design. Therefore Specific Calculation method namely recurrence model is used. This model is based on the change rate in the RC radioactivity materials and operational characteristics of SMART. Calculation results show tremendously increase of the levels of RC activity because no cleanup of RC and long term operation.

1. Introduction

The ongoing nuclear program in Korea is only for large-scale electricity generation. Use of nuclear energy for other than electricity generation is being considered in the areas of district heating, cogeneration, desalination and process heat production. In this aspect, the System-Integrated Modular Advanced Reactor (SMART) which is a 330 MWt-sized multi-purpose integral-type reactor is under development.[1]

As a part of its development program, various radiological safety and environmental assessments of SMART have been performed, which requires the best estimation of radioactive source terms. Based upon the results of assessment, appropriate design modifications will be recommended for enhancement of its safety and mitigation of its environmental impacts.

SMART is different from conventional reactor concepts in operation and design. For instance, SMART adopts the one-batch core operation in which the whole core is replaced, i.e., the refueling takes place in every five years. The operation will significantly increase the inventories of long-lived fission product in the core since a long-lived isotope never reaches an equilibrium state in five years. SMART also adopts the soluble boron-free operation in the reactor coolant system for reactivity control, and no cleanup of reactor coolant(RC) is employed via recirculation during normal plant operation. The operation will tremendously increase the levels of RC activity.

During reactor operation, fission products generate inside the fuel. Hence, the increased inventories of core activity will impose higher risk to the public following the postulated accidents including severe accidents and loss-of-coolant accidents. Small amounts of radioactive fission product are released from the fuel to the reactor coolant system through defective claddings, which will be eventually exposed to release into the environment. Hence, it is very important to predict the amounts of core activities as well as RC activities, which will be eventually used to compute various source terms.

The purpose of this study is to estimate the source terms of SMART, more specifically, core and RC activities for accident analysis, radwaste treatment system design, ventilation system design, shielding evaluation, and environmental assessment. Major efforts are concentrated on estimating the inventories of long-lived fission product.

2. Radioactive Source Terms

There are four radioactive source terms discussed here. They include: accident source term, design RC source term, expected RC source term, and shielding source term.

2.1. Accident Source Term

As one of reactor siting criteria, the accident source term is used for the determination of exclusion area (EA) and low population zone (LPZ). The accident source term is also used for designing the containment air purification system, setting the containment leakage rate, designing the control room habitability system, and qualifying the equipment in the containment following accident conditions.

There are two kinds of accident source term accepted by licensing bodies at present according to release modes of core activity: instantaneous and time-dependent releases. The instantaneous release of core activity is based upon TID-14844[2], and the time-dependent release is based upon NUREG-1465[3]. Both documents suggest each isotopic release as the fraction of maximum core activity. Hence, the maximum core activity should be computed at the end of five-year operation of SMART.

2.2. Design RC Source Term

The design RC source term is composed of the activities in the reactor coolant system which are computed assuming 1% failed fuel fraction. The source term is used for assessing the environmental consequences following the accidents involving RC release in the conservative accident analyses of the safety analysis report. It is also used in designing radwaste treatment systems and in determining life-time integrated doses of certain station equipment.

2.3. Expected RC Source Term

There are two kinds of expected RC source term in accordance with failed fuel fraction: 0.12% and 0.5%. The former is used for the evaluation of annual environmental impact during normal plant operation while the latter for realistic accident analyses of the environmental report.

2.4. Shielding Source Term

The source term used for shield design consists of the RC activities based upon full power operation with 0.25% failed fuel fraction and no on-line gas stripping.

3. Source Term Assessment

The accident source term is obtained from the core activity, and the rest of source terms are obtained from the RC activity.

3.1. Core Activity

As a reactor starts its operation, fission products begin to generate in the core. The rate of change in the number of fission product nuclide i of the core is simply given by

$$\begin{aligned}\frac{dN_i}{dt} &= \gamma_i \int_V d\underline{r} \int_E dE\, \Sigma_f(\underline{r}, E)\,\phi(\underline{r}, E) \\ &- \lambda_i N_i \\ &- \int_V d\underline{r} \int_E dE\, \Sigma_{ai}(\underline{r}, E)\,\phi(\underline{r}, E)\end{aligned} \tag{1}$$

where

N_i number of fission product nuclide i in the core,

γ_i fission yield of nuclide i,

$\Sigma_f(\underline{r}, E)$ macroscopic fission cross section, cm^{-1},

$\phi(\underline{r}, E)$ differential neutron flux, n/sec · cm^{2}MeV,

λ_i nuclear transformation constant of nuclide i, sec^{-1}, and

$\Sigma_f(\underline{r}, E)$ macroscopic absorption cross section of nuclide *i*, cm^{-1}.

The rate of change in the number of activation product nuclide i of the core is simply given by

$$\begin{aligned}\frac{dN_i}{dt} &= \int_V d\underline{r} \int_E dE\, \Sigma_{act}{}^i(\underline{r}, E)\,\phi(\underline{r}, E) \\ &- \lambda_i N_i \\ &- \int_V d\underline{r} \int_E dE\, \Sigma_{ai}(\underline{r}, E)\,\phi(\underline{r}, E)\end{aligned} \tag{2}$$

where, $\Sigma^i_{act}(\underline{r}, E)$ = macroscopic activation cross section which produces nuclide i, cm^{-1}.

As the time goes by, short-lived radionuclides will be saturated, but long-lived ones will continue to increase without reaching equilibrium states. In this study, ORIGEN-2[4] is used for the simulation of nuclear fuel cycle and computation of nuclide compositions in the core. The core activities are computed for various fuel burnup values, i.e., in different time steps of reactor operation.

3.2. Reactor Coolant Activities

The rate of activity change of nuclide i in the reactor coolant is given by

$$\begin{aligned}\frac{dC_i}{dt} &= \frac{P_i(t)}{WP} - \frac{L_i}{WP} C_i(t) \\ &- (R_i + \lambda_i + \sigma_{ai}\phi) C_i(t)\end{aligned} \tag{3}$$

where

C_i activity of nuclide i in the reactor coolant, Ci/kg,

P_i release rate of nuclide i from the core to the reactor coolant, Ci/sec,

WP RC inventory, kg,

L_i RC leakage rate, kg/sec,

R_i RC purification rate, sec^{-1},

σ_i microscopic absorption cross section of nuclide i, cm^2, and

ϕ average neutron flux, n/sec · cm^2.

The release rate of nuclide i, P_i is proportional to its core activity. For fission products, it is also a function of failed fuel fraction and escape rate coefficient. For activation products, it is a function of corrosion rate and crud burst mechanism. For a long-lived fission product, the release rate of nuclide i is a time-dependent function since its core activity varies with respect to time. SMART does not have RC purification (R_i = 0), and neglecting the RC leakage term, Eq. 3 becomes, except Xe-135 ($\sigma_{ai} \cdot \phi \ll \lambda_i$),

$$\frac{dC_i}{dt} = \frac{P_i(t)}{WP} - \lambda_i C_i(t) \tag{4}$$

Let' s assume the values of $P_i(t)$ be known at t = t_i,

Table 1. Time-Dependent Variation of Core Activities (Curies)

Isotopes	Kr-85	I-131	Cs-137	Y-91	Zr-95
Half Life(sec)	3.392E+08	6.930E+05	9.483E+08	5.055E+06	5.531E+06
325.0Day	2.91E+03	5.99E+05	2.52E+04	1.06E+06	1.21E+06
365.0Day	2.89E+03	1.96E+04	2.52E+04	6.62E+05	7.81E+05
690.0Day	5.43E+03	6.02E+05	4.99E+04	9.87E+05	1.18E+06
730.0Day	5.40E+03	1.97E+04	4.97E+04	6.19E+05	7.64E+05
1055.0Day.	7.64E+03	6.07E+05	7.39E+04	9.21E+05	1.14E+06
1095.0Day	7.59E+03	1.99E+04	7.38E+04	5.77E+05	7.39E+05
1420.0Day	9.57E+03	6.13E+05	9.75E+04	8.60E+05	1.11E+06
1460.0Day	9.50E+03	2.01E+04	9.72E+04	5.39E+05	7.16E+05
1760.0Day	1.11E+04	6.23E+05	1.19E+05	8.07E+05	1.07E+06

$t_2, \cdots, t_{n-1}, t_n, \cdots, t_N$. For a given time interval ($t_{n-1} \sim t_n$) , assuming a constant release rate, $P_{i,n}=P_i\ (t_n)$, the RC activity becomes

$$C_i(t) = \frac{P_{i,n}}{\lambda_i WP}(1 + C\exp(-\lambda_i t)) \qquad (5)$$

where

$$C = C_i(t_{n-1})\frac{\lambda_i WP}{P_{i,n}} - 1 \qquad (6)$$

Inserting Eq. 6 into Eq. 5, the RC activity becomes

$$C_i(t) = \frac{P_{i,n}}{\lambda_i WP}(1 - \exp(-\lambda_i t)) + C_i(t_{n-1})\exp(-\lambda_i t) \qquad (7)$$

Using Eq. 7, the RC activity at the end of each time division could be recurrently found starting from the first time interval.

4. Results of Study

4.1. Core Activities

In SMART, nuclear fuels will stay inside the reactor for five years of continuous operation, and the whole core will be replaced by a new batch after the five-year irradiation. The average U-235 enrichment of charged fuel is 5% at the beginning of cycle. For this study, a 40-day maintenance and repair is assumed every year following a 325-day continuous reactor operation.

Table 1 summarizes the core activities of five major fission products for SMART at different time steps, which are computed using ORIGEN-2. And Table 2 shows the maximum core activities of SMART, which occurs at the end of 5-year reactor irradiation. In Table 2, they are also compared with those of Kori Unit 1. Values in table are sum of the isotopes inventory

As shown in Tables 1 and 2, due to long reactor irradiation, the core activities of long-lived fission product become very high in spite of its low power level. For example, after 5-year operation, the maximum core inventory of Cs, which is one of the most controlling isotopes in the accident source term, is 46.974 kg, while that of Cs for Kori Unit 1 is 87.998 kg[5]. Considering that the power level of Kori Unit 1 is six times bigger than that of SMART, the specific core inventory of Cs is more than three times bigger in SMART.

Table 2. Maximum Core Inventory of Fission Products

Isotope	Kori #1 (kg)	SMART (kg)	Isotope	Kori #1 (kg)	SMART (kg)
Se	1.860	0.937	Ag	2.177	0.903
Br	0.726	0.359	Sb	1.043	0.413
Kr	12.383	6.343	Te	15.014	7.179
Rb	11.476	5.976	I	7.666	3.497
Sr	31.933	15.558	Xe	169.646	79.873
Y	16.375	8.176	Cs	87.998	46.974
Zr	129.276	59.636	Ba	44.906	23.324
Nb	2.041	0.374	La	39.645	19.802
Mo	102.514	52.646	Ce	93.442	42.010
Tc	25.220	12.403	Pr	34.519	17.979
Ru	74.390	34.775	Nd	114.307	61.907
Rh	13.517	6.274	Pm	6.169	1.990
Pd	32.342	16.320	Sm	19.958	11.699

4.2. RC Activities

SMART does not employ the RC cleanup system during normal plant operation. However, towards the end of every 1-year reactor operation, the plant will shut down for maintenance and repair work, in which the complete cleanup of reactor coolant will automatically take place prior to the next startup.

For recurrence computation, the time period of each 1-year reactor operation is divided into 12 time intervals. In the fifth year, however, the number of time intervals is increased to improve the accuracy of computation, and the computation is performed for every 25-day interval. Table 3 shows design and expected RC activities of SMART at various time intervals during the last year of fuel batch operation, with and without on-line RC purification system. It is assumed to have the RC purification rate of 2.0×10^{-5} sec^{-1}, which is the same as that of YGN Unit 3[6] and other plant built after that in korea.

Table 4 summarizes the design RC source term of SMART which is defined as the maximum activities in the reactor coolant computed using 1% failed fuel fraction. This source term is computed on the assumption and method described before. Also This is compared with that of YGN Unit 3 in Table 4.

5. Conclusions

The difference in plant design affects source terms. The long refueling period and no RC cleanup definitely produce higher source terms in SMART, which could require certain modifications for decrease these source terms in the present system designs of SMART. For example, cleanup filter at the steam generator or extra radioactivity gas tank in the vessel is able to be thought.

The effects of increased accident source term could come into play in sizing EA and LPZ, designing the containment systems such as containment air purification system and containment leakage rate, and qualifying

Table 3. Design and Expected RC Activities (with and Without RC Cleanup)

	Design Source Terms (1% failed fuel)					Expected Source Term (0.12% failed fuel)				
isotope	Kr-85	I-131	Cs-137	Y-91	Zr-95	Kr-85	I-131	Cs-137	Y-91	Zr-95
Half life(sec)	3.392E+08	6.930E+05	9.483E+08	5.055E+06	5.531E+06	3.392E+08	6.930E+05	9.483E+08	5.055E+06	5.531E+06
day					without purification					
1460	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
1485	1.838E+02	8.821E+02	3.778E+02	2.521E-01	3.357E-01	2.205E+01	1.059E+02	4.534E+01	3.025E-02	4.029E-02
1510	3.694E+02	1.089E+03	7.619E+02	4.655E-01	6.230E-01	4.433E+01	1.307E+02	9.143E+01	5.586E-02	7.476E-02
1535	5.568E+02	1.126E+03	1.152E+03	6.432E-01	8.657E-01	6.682E+01	1.351E+02	1.383E+02	7.718E-02	1.039E-01
1560	7.461E+02	1.131E+03	1.549E+03	7.896E-01	1.069E+00	8.953E+01	1.357E+02	1.859E+02	9.475E-02	1.283E-01
1585	9.371E+02	1.133E+03	1.952E+03	9.085E-01	1.238E+00	1.125E+02	1.360E+02	2.342E+02	1.090E-01	1.485E-01
1610	1.130E+03	1.136E+03	2.361E+03	1.004E+00	1.376E+00	1.356E+02	1.363E+02	2.833E+02	1.205E-01	1.651E-01
1635	1.321E+03	1.137E+03	2.776E+03	1.079E+00	1.489E+00	1.589E+02	1.365E+02	3.331E+02	1.295E-01	1.787E-01
1660	1.521E+03	1.139E+03	3.197E+03	1.138E+00	1.581E+00	1.825E+02	1.367E+02	3.837E+02	1.366E-01	1.897E-01
1685	1.719E+03	1.141E+03	3.625E+03	1.184E+00	1.654E+00	2.062E+02	1.369E+02	4.350E+02	1.421E-01	1.985E-01
1710	1.918E+03	1.142E+03	4.059E+03	1.218E+00	1.714E+00	2.302E+02	1.371E+02	4.871E+02	1.462E-01	2.056E-01
1735	2.119E+03	1.144E+03	4.499E+03	1.244E+00	1.760E+00	2.543E+02	1.372E+02	5.399E+02	1.492E-01	2.112E-01
1760	2.322E+03	1.106E+03	4.945E+03	1.253E+00	1.785E+00	2.786E+02	1.327E+02	5.934E+02	1.504E-01	2.142E-01
					with purification					
1460	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
1485	4.263E+00	4.748E+01	8.753E+00	6.696E-03	8.815E-03	5.115E-01	5.698E+00	1.050E+00	8.036E-04	1.058E-03
1510	4.325E+00	5.316E+01	8.910E+00	7.385E-03	9.633E-03	5.189E-01	6.379E+00	1.069E+00	8.862E-04	1.156E-03
1535	4.386E+00	5.384E+01	9.070E+00	7.888E-03	1.025E-02	5.264E-01	6.461E+00	1.088E+00	9.466E-04	1.230E-03
1560	4.446E+00	5.389E+01	9.229E+00	8.268E-03	1.072E-02	5.335E-01	6.467E+00	1.107E+00	9.921E-04	1.287E-03
1585	4.508E+00	5.397E+01	9.388E+00	8.535E-03	1.108E-02	5.410E-01	6.476E+00	1.127E+00	1.024E-03	1.330E-03
1610	4.570E+00	5.409E+01	9.547E+00	8.718E-03	1.134E-02	5.484E-01	6.491E+00	1.146E+00	1.046E-03	1.361E-03
1635	4.627E+00	5.418E+01	9.706E+00	8.840E-03	1.154E-02	5.553E-01	6.501E+00	1.165E+00	1.061E-03	1.384E-03
1660	4.689E+00	5.425E+01	9.865E+00	8.916E-03	1.168E-02	5.627E-01	6.510E+00	1.184E+00	1.070E-03	1.401E-03
1685	4.747E+00	5.433E+01	1.002E+01	8.957E-03	1.177E-02	5.696E-01	6.519E+00	1.203E+00	1.075E-03	1.413E-03
1710	4.804E+00	5.440E+01	1.018E+01	8.973E-03	1.185E-02	5.765E-01	6.528E+00	1.222E+00	1.077E-03	1.422E-03
1735	4.862E+00	5.447E+01	1.034E+01	8.971E-03	1.189E-02	5.834E-01	6.537E+00	1.241E+00	1.077E-03	1.427E-03
1760	4.910E+00	5.241E+01	1.049E+01	8.718E-03	1.161E-02	5.892E-01	6.289E+00	1.259E+00	1.046E-03	1.393E-03

Table 4. Design RC Activities

Isotopes	λ (/sec)	C (max) (Ci)	YGN (Ci)	Isotopes	λ (/sec)	C (max) (Ci)	YGN (Ci)
Kr-85m	4.297E-05	3.534E+01	1.544E+02	Sr-90	7.635E-10	2.982E+00	1.970E-02
Kr-85	2.043E-09	2.322E+03	2.875E+00	Sr-91	1.999E-05	5.325E-02	9.584E-01
Kr-87	1.514E-04	1.935E+01	1.597E+02	Y-91m	2.323E-04	4.254E-04	5.324E-01
Kr-88	6.778E-05	6.084E+01	3.780E+02	Y-91	1.371E-07	1.253E+00	7.454E-02
Xe-131m	6.774E-07	9.133E+01	3.035E+01	Y-93	1.891E-05	1.116E-02	2.236E-02
Xe-133m	3.662E-06	9.607E+01	8.519E+00	Zr-95	1.253E-07	1.785E+00	8.519E-02
Xe-133	1.530E-06	7.414E+03	4.100E+03	Nb-95	2.293E-07	1.007E+00	7.986E-02
Xe-135m	7.554E-04	2.908E+00	1.278E+02	Mo-99	2.919E-06	1.101E+02	4.898E+01
Xe-135	2.106E-05	2.037E+02	5.857E+02	Tc-99m	3.203E-05	7.031E-03	2.502E+01
Xe-137	3.025E-03	3.264E+00	3.035E+01	Ru-103	2.043E-07	1.007E+00	2.928E-02
Xe-138	8.203E-04	1.147E+01	1.118E+02	Ru-106	2.147E-08	1.381E+00	1.012E-02
Br-84	3.632E-04	6.825E-01	4.313E+00	Te-129m	2.387E-07	1.677E+01	1.012E+00
I-131	1.000E-06	1.106E+03	4.153E+02	Te-129	1.659E-04	1.593E-01	1.171E+00
I-132	8.388E-05	1.893E+01	1.331E+02	Te-131m	6.417E-06	1.892E+00	5.058E+00
I-133	9.255E-06	2.445E+02	6.389E+02	Te-131	4.620E-04	1.624E-01	2.183E+00
I-134	2.196E-04	1.132E+01	9.051E+01	Te-132	2.503E-06	4.807E+01	3.408E+01
I-135	2.930E-05	7.211E+01	3.940E+02	Ba-137m	4.526E-03	3.378E-05	4.845E+01
Rb-88	6.496E-04	1.290E+00	3.887E+02	Ba-140	6.290E-07	2.421E+00	6.922E-01
Cs-134	1.066E-08	5.382E+03	3.567E+01	La-140	4.780E-06	5.185E-02	2.023E-01
Cs-136	6.095E-07	1.412E+02	7.986E+00	Ce-141	2.468E-07	9.528E-01	2.502E-02
Cs-137	7.308E-10	4.945E+03	5.111E+01	Ce-143	5.826E-06	3.663E-02	7.454E-02
Sr-89	1.587E-07	5.403E+00	5.324E-01	Ce-144	2.815E-08	3.363E+00	5.857E-02

equipment following accident conditions.

No cleanup will tremendously increase the levels of RC activity. The compliance with ALARA requirements in determining effluent releases during normal plant operation is assessed using the expected RC source term. The preliminary assessment suggests the employment of on-line RC cleanup in SMART during normal plant operation. Radwaste treatment systems should be also assessed for their design safety classifications and seismic categories using the design RC source term in accordance with the requirements set forth in appropriate regulations.

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